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INSTRUMENTATION FOR OPTICAL OCEAN REMOTE SENSING

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ABSTRACT

Instruments used in ocean color remote sensing algorithm development, validation, and data acquisition with potential for further commercial development and marketing will be discussed.

The Ocean Data Acquisition System (ODAS) is an aircraft-borne radiometer system, suitable for light aircraft, has applications for rapid measurement of chlorophyll pigment concentrations along the flight line. The instrument package includes a three channel radiometer system for upwelled radiance, an infrared temperature sensor, a three channel downwelling irradiance sensor, and Loran-C navigation. Data are stored on a PC aboard and processed to transects or interpolated "images" on the ground. The instrument has been in operational use for two and a half years, most extensively (over 35 missions) with the NOAA Chesapeake Bay Program, but also in NASA missions in the North Atlantic, Iceland, and off Brazil. The accuracy of pigment concentrations from the instrument is quite good even in complex Chesapeake Bay waters.

To help meet the requirement for validation of future satellite missions, a prototype air-deployable drifting buoy for measurement of near-surface upwelled radiance in multiple channels is currently undergoing test deployment. The optical drifter burst samples radiance, stores and processes the data, and uses the Argos system as a data link. Studies are underway to explore the limits to useful lifetime with respect to power and fouling. There is also high potential for development of simple, highly reliable sensors for optical radiance measurements from underway vessels.

INTRODUCTION

The marine phytoplankton play an important role in the Earth's carbon cycle, and recent technology has provided the means to observe the marine biosphere in surface layers at global and monthly periods. Absorbance of light by chlorophyll pigments involved in photosynthesis causes a shift in peak reflectance from blue to green as the amount of phytoplankton increase which is readily detected by satellite ocean color sensors. Application of satellite visible remote sensing is essential to understand the spatial and temporal distributions of the marine biosphere, but is only one part of a complete observing system. Measurements from aircraft, ships, and in-situ observations are also crucial to understand the cycles of marine phytoplankton, the marine food web, and the role of the marine biosphere in global carbon and climate cycles. Development of supporting technology within the commercial sector is crucial to overcome the tremendous sampling challenge presented by the oceans. This paper describes two systems under development at Goddard which fill critical sampling needs for quantifying the satellite observations and which are felt to have significant commercial potential.

THE OCEAN DATA ACQUISITION SYSTEM (ODAS): APPLICATION TO CHESAPEAKE BAY

NASA research has shown the utility of remotely sensed radiance for measuring chlorophyll plant pigment concentration for oceanic research programs. Between the demise of the Coastal Zone Color Scanner in June, 1986, and the flight of a follow-on sensor in the early 1990's, scientists are dependent upon aircraft sensors for contemporary data. Aircraft sensors also typically provide higher spatial and temporal coverage than satellite sensors, and so will always be an important complement to ship, buoy, and satellite observation systems. While several research ocean color instruments are available within federal laboratories, there is currently no simple, commercially-available instrumentation available for routine scientific use. This section describes the development and application of a nadir viewing radiometer system developed for monitoring chlorophyll pigments.

One approach to measuring phytoplankton biomass on the time and space scales of importance is remote sensing from aircraft and satellite to determine spectral properties that are responsive to pigment concentrations (Esaías, 1980). Remote sensing of chlorophyll pigment concentrations using satellite and aircraft sensors has matured during the last decade, but this technology has principally been applied to the open ocean where phytoplankton dominate the optical signal. Less work has been done in optically more complex waters typical of estuaries, principally because algorithms for deriving pigment concentrations there are very dependent upon other water optical properties. Since the relative optical characteristics vary greatly from one estuary to another, and with time, local algorithms must be developed and validated for optimal results.

Extensive use of aircraft ocean color instruments has been made by NASA and NOAA scientists (Campbell & Thomas 1981; Hoge & Swift 1981; Campbell & Esaías 1983, 1985; Campbell et al. 1986; Hoge et al. 1986, 1987). These studies encompass a variety of water types, including some Case 2 waters (coastal, estuarine) and both "active" and "passive" systems. Active systems measure laser-induced fluorescence of chlorophyll; passive systems measure upwelled radiance. Many of the existing systems, especially active systems, are quite large and/or have requirements necessitating the use of a large aircraft. Costs are prohibitive for programs such as Biomonitoring that require frequent and regular sampling.

System Description

The Ocean Data Acquisition System is a low-cost instrument with potential commercial application. It is easily installed in small aircraft and flown over the coastal zone ocean to remotely measure sea surface temperature and three channels of ocean color information. From this data, chlorophyll levels can be derived for use by ocean scientists, fisheries, and environmental management. Data can be transmitted to ships for real-time use with other measurement and sampling objectives.

The optical portion of the system has three primary instruments: an IR radiometer to measure surface temperature, a three-channel visible spectro-radiometer viewing the water, and a three channel sky sensor mounted on top of the aircraft to monitor incident irradiance. The down looking radiometer channels have a field of view of 2 degrees, and measure upwelled radiance at 460, 490, and 520 nanometers (blue, blue-green, and greenish blue) in 15 nm bands. The outputs are fed into a PC based data system where they are digitized to 12-bit resolution, formatted, and recorded on a hard disk. All parameters, including spectral curvature used for chlorophyll calculation, are displayed on the monitor. The operator controls the external shutters, gain, and starts and stops data recording from the keyboard. Radiometric data are sampled every 0.1 sec, which at typical flight speeds, corresponds to sampling distances of from

5-10 meters. The aircraft package contains a LORAN-C unit for aircraft location information (updated every 8 seconds), on-board data processor and formatter, digital cassette tape recorder, . The initial storage of data is as binary files uniquely designated by the time of their creation. A typical file from the applications discussed includes a record of 2 to 15 minutes duration corresponding to an individual flight line, with smaller files being produced in cross-estuary tracks and larger files in along-axis tracks.

The data telemetry system is based on a packet radio terminal controller, and radio transceiver for data transmission to a ship. From the measurement flight altitude of 500 ft., the line of sight transmitter range to a ship is about 30 miles. The VHF transceiver can also be used for voice communication and coordination between aircraft and ship. Digital data rates are about 1200 baud.

The shipboard package contains a transceiver packet terminal controller, data processing capability, cassette tape recorder, and printer. Both raw data and chlorophyll concentrations are available for real-time analysis, and these data can be shown in latitude and longitude coordinates on a screen map. The shipboard package has not been used as much as initially planned, since the emphasis to date has been on monitoring rather than support of real-time experiments.

To keep down the cost of reproducing the instrument system, commercially available subsystem components are principally used. Standard camera lenses for the optical systems, amateur radio packet controllers, and modified amateur transceivers (modified to FCC assigned ODAS frequencies) for the data transmission systems, and rack mountable personal computers for the data systems are examples. The detector assembly was designed at GSFC. The detectors, filters, and preamplifiers are in a temperature-controlled housing to maintain radiometric stability. The sky sensors are modified from commercially available cosine collectors. A thermistor is use to monitor the sky sensors to correct for their temperature response.

Data processing on the ground has been performed on PC's, MacIntosh, and Sun computers. The principle functions are 1) calculation of navigation coordinates from the 8 second Loran data to match the more frequent radiometric data, 2) eliminating individual points contaminated by sun glitter through screening based on sample variance, 3) application of calibration and pigment algorithms, 4) merging the navigation with averaged, glint free data, 5) contouring and displaying the data using various packaged programs.

Two algorithms have been used to process the radiance data from ODAS. The system was designed to exploit the "curvature" algorithm discovered by Grew (1981) at NASA's Langley Research Center. The curvature algorithm:

$$\log (\text{Chl}) = a - b \log [(L_2)^2 / (L_1 * L_3)]$$

where L_n represents the radiance detected in channel n , and a and b are system coefficients, is very amenable to the ODAS objectives, since it minimizes the need for atmospheric correction and is less sensitive to variations in other water constituents than other approaches (Campbell and Esaias, 1983). The coefficients a and b are initially derived from comparisons with in-situ data, but thereafter ODAS does not depend upon the availability of sea-truth. Since the conversion of digital counts to radiance is a linear function, the algorithm can be applied to raw data (using slightly different coefficients).

Secondly, algorithms using ratios of channels can also be used provided attention is paid to the variations in optical properties other than in-water pigment concentration. Development of band-ratio algorithms for estuarine systems would be greatly enhanced by the addition of spectral bands corresponding to those planned for future ocean color satellites.

Ocean color algorithms, and curvature algorithms in particular, require high precision radiometry, and can tolerate very little drift between channels as a function of time. Repeated calibration using the GSFC hemisphere radiance source has shown precision at the 0.2% level between missions and channels. Absolute radiometric accuracy of the system is estimated at 7%, primarily a function of the accuracy of the hemisphere source. The signal to noise ratio is greater 2400:1.

System Test and Evaluation

The ODAS system was tested on the Wallops P3-A Orion during development on a series of 4 missions including the Arctic Ocean Expedition in May 1987. An example of comparisons of ODAS observations with simultaneous NASA WFF Airborne Oceanographic Lidar values are given as Fig. 1. The correlation coefficient (r) for the chlorophyll signals in this example was 0.97. These data were obtained between the Gulf Stream and the coast off Wallops Island, Va. in March 1988. This high degree of correlation is typical for the performance of curvature algorithms in ocean waters, however further testing was required to determine how well the ODAS and curvature algorithms performed in more turbid estuarine waters.

In July and September, 1988, the ODAS was used by a group of investigators from the Virginia Institute of Marine Sciences, The Chesapeake Bay Institute, University of Delaware, and NOAA to overfly portions of the Chesapeake and Delaware Bays (Harding, 1988). The objective of these flights were to test ODAS performance in the more turbid estuarine waters, to demonstrate ODAS utility as an operational sensor in the Chesapeake Bay monitoring program, and to demonstrate a transfer of technical capability from NASA to academic investigators. The ODAS was flown on the VIMS aircraft, a DeHaviland Beaver, and was operated by the investigators. About 25 megabytes of data from the flights were analyzed by scientists from the three institutions.

Based upon the success demonstrated in the initial program, Drs. L. W. Harding and E. C. Istweire of The Johns Hopkins Chesapeake Bay Institute, with funding from the NOAA Coastwatch Program, led a team of investigators in conducting a more ambitious series of flights in 1989 and 1990 (Harding and Istweire, 1990). The purpose of these flights was to monitor phytoplankton dynamics in the central and lower Bays during the spring and summer, and observe the response of the Bay's phytoplankton to river runoff, as well as provide a more thorough assessment of ODAS and a single set of algorithm coefficients.

One clearly identified problem in the Chesapeake Bay, similar to other impacted estuaries, is an elevated input of dissolved inorganic nutrients and a concomitant increase in the biomass of microscopic algae (Boynton et al. 1982; D'Elia et al. 1986; Harding et al. 1986; Correll 1987; Fisher et al. 1988). The phytoplanktonic algae accumulate to very high concentrations in spring as they use nutrients and light for to produce more algal biomass through photosynthesis. Part of the highly publicized cleanup effort in the Bay involves reduction of nitrogen and phosphorus inputs with the goal of reducing algal biomass by the turn of the century. The detection of responses of phytoplankton biomass densities to this effort is, therefore, an important element of the attempt to improve water quality and reclaim lost productivity.

Bay-wide Biomonitoring Programs have been developed by the states of Maryland and Virginia to track changes in physical, chemical and biological characteristics of the estuary that are expected to occur as results of the cleanup effort. Among the parameters that are monitored are chlorophyll a as a measure of algal biomass, and water transparency to determine the depth of the photic layer, the part of the water column in which active photosynthesis occurs. While these surveys generate data to provide twice monthly snapshots of conditions in the Chesapeake as a whole, they are restricted in time and space by expense and logistics. It is likely that ephemeral or localized events, such as algal blooms that may persist for only days to weeks, are missed or undersampled because of the Bay's size and complexity. To date, no affordable alternative to shipboard monitoring has been used to assess the size and longevity of these event-scale phenomena. The importance of phytoplankton blooms lies in the tremendous amount of organic carbon associated with them and in the link of this primary production to other processes, among them nutrient utilization, fisheries productivity, and the seasonal development of anoxic conditions.

A total of 16 flights covering the Bay were conducted between mid March and mid July 1989. Improved data processing procedures were developed using an image workstation. ODAS observations were compared with the extensive in-situ Bay monitoring data when they were coincident within two days and 0.01 degrees latitude and 0.005 degrees longitude (about 5 km by 7km). These wide limits were chosen to maximize the number of comparison points, and are much larger than ideal sea-truth comparison criteria. The results of the comparison are shown in Figure 2. The RMS deviation was found to be 0.243 log pigment concentration, or a factor of 1.7. Considering the broad limits place on temporal and spatial coincidence, widely diverse atmospheric and water optical conditions during the measurement period, this fit to a single set of algorithm coefficients is very pleasing. When sufficient contemporaneous aircraft and ship data permit the derivation of time and region specific coefficients, the fit is of course much tighter, as evidenced by figure 1.

Figure 3 is an example of pigment concentration patterns observed with the ODAS sensor produced using an objective interpolation between ODAS flight lines. The distributions clearly indicate higher spatial variability than could be sampled using only in-situ stations. The overall patterns of pigment distribution in 1989 were substantially different from recent annual patterns, a result of anomalous phasing of peak river flow bringing freshwater, nutrients, and sediment into the Bay. Also, a very tight relationship between surface chlorophyll concentrations and integrated chlorophyll content of the total water column, using digital bathymetry for the Bay, was another key finding of the demonstration. This relationship can be used to calculate the total phytoplankton biomass in the Bay, of direct importance to anoxia studies, using only remotely sensed surface concentrations.

An even larger number of monitoring flights (22) were conducted in 1990 jointly with VIMS personnel. Analysis and comparison of those data with in-situ Biomonitoring data still underway due to the longer time to reduce the in-situ data sets.

Operation of the sensor in a vigorous program such as the Chesapeake Bay Coastwatch Program revealed the need for several improvements which have been implemented in the data logging system, including faster updating of Loran data. The Beaver aircraft, very cost effective and capable of slow cruising speeds, proved to be an adequate platform. However, its single engine makes it a bit unsuitable for coastal ocean flights. Additionally, since the ODAS was mounted on the centerline within the fuselage, some difficulties were experienced with stray oil droplet deposit on the radiometer windows. Although no pronounced effect on radiometric data quality was apparent, it was virtually eliminated by raising the mounts so that the sensor was further away from the airstream.

Comparisons of surface temperature with the infrared radiometer indicate an accuracy of from 0.5 to 1.0 degree, which is consistent with errors in making such measurements due to variations in haze and humidity, and in comparing bulk water temperatures with skin brightness temperatures.

The NASA GSFC role in these and future uses of the ODAS is primarily one of assuring instrument capability and calibration, and consultation on data analysis. Investigators provide funding, a suitable aircraft, arrange for installation, mission logistics, and data analysis. The demand for cost effective ocean color sensors with modest computing requirements for data reduction is growing. The ODAS system was used to collect ocean color data during the CITE-3 missions off the East Coast of the US and Northeast South America. The data, collected from the NASA Electra, is being used to provide a measure of ocean biogenic trace gas sources for the atmospheric chemistry program. Data are being analyzed by Dr. P. Matrai at University of Miami. During summer of 1991, ODAS will be used in an introductory marine remote sensing course for undergraduates sponsored by the University of Maryland Sea Grant Office, in conjunction with the Bay Monitoring Program. Additionally, GSFC PI's plan to use the ODAS on occasion for their own ocean color research programs.

EXPENDABLE OPTICAL DRIFTING BUOY FOR SATELLITE OCEAN COLOR SENSOR VALIDATION

The objective of this GSFC Director's Discretionary Fund project is to develop and test a low-cost optical drifter for validation of satellite ocean color observations from the planned SeaWiFS and EOS missions, and to evaluate its reliability and the methodology for using such observations in sensor validation. Calibration and knowledge of temporal change of satellite visible radiometers to the accuracy and precision demanded for colorimetry of the ocean exceeds proven capability of pre-launch and on-board techniques. While absolute calibrations are improving, "vicarious" calibration procedures which include atmospheric correction algorithms and ocean bio-optical observations will remain essential. To be most useful for monitoring satellite sensor performance, these observations should be available from a global array within a short time period. There is no optical measurement data base for use with ocean color radiometry comparable to the international SST network. We hope that this DDF activity will help define required system design and performance characteristics, and elicit private sector interest in development of commercial units for the research application use.

Our approach is to build a prototype unit and test this in a tethered mode this winter, followed by deployment of up to four units in drift mode later this year. Designs have been developed which will return observations made at <30 min intervals during the day via the ARGOS system. The observations include a) incident surface irradiance (E_{0+}) over 400 - 700 nm; b) upwelled radiance (L_u 1m) at 460, 490, and 520 nm; and c) sea surface or buoy temperature. Only three channels were selected for the prototype because a small three channel radiometer was available from previous programs, and to live within transmission bandwidth constraints. Increasing the number of spectral channels to 6 or 8 is recommended for future units. The choice of the wavelengths for the bands is based on the ODAS and curvature algorithm experience; future systems should better match the spectral bands planned for future ocean color satellites. Based on relationships of spectral radiance and spectral attenuation, L_u 1m, λ can be propagated to the surface to compute spectral reflectance (R_λ to estimate pigment concentration) and water-leaving radiance (L_w , λ for comparison with satellite or aircraft data). The stated objective in satellite sensor programs is to derive L_w , λ to within $\pm 5\%$ precision.

The drifter prototype package is about 1.2 m long by 15 cm diameter, and is compatible with air-deployment. Life expectancy is 4-6 months. Creative sampling, data processing and compression, and transmitter control are used to maximize information return. The prototype unit is currently undergoing full end to end test of the optics, data processing, and data transmission systems on the roof at GSFC.

The area of greatest risk scientifically is lack of knowledge of calibration and precision of the radiometer due to biofouling of the submerged optical windows. Organic tin compounds have been used to coat windows on optical moorings successfully, and test windows and prototype drifter housing with biofoulant coated windows are undergoing further testing by the Navy's David Taylor Research Center in Annapolis and San Diego. Growth must also be prevented everywhere to prevent changes in buoyancy.

Interrogating store and forward satellite data collection systems, planned by several groups, for testing in the next few years would be a very attractive alternate to ARGOS for future versions. Higher data volumes, reduced power consumption, and precise simultaneity with satellite overpasses are expected benefits.

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Figure Captions

Figure 1. Comparison of chlorophyll pigment signals from ODAS and the Airborne Oceanographic Lidar (AOL) off Wallops Island, VA. Chlorophyll pigment concentrations were estimated to range from 0.1 to 5 mg/cubic meter.

Figure 2. Linear regression of log surface pigment concentration collected by the Biomonitoring Program in 1989 on ODAS -log G. From Harding and Itsweire, 1990.

Figure 3. Interpolated map of surface chlorophyll concentration from ODAS track data. Dark areas were not sampled. The aircraft was excluded from the Patuxent Naval Air Station restriction zone in the central Chesapeake on this date. From Harding and Itsweire, 1990.

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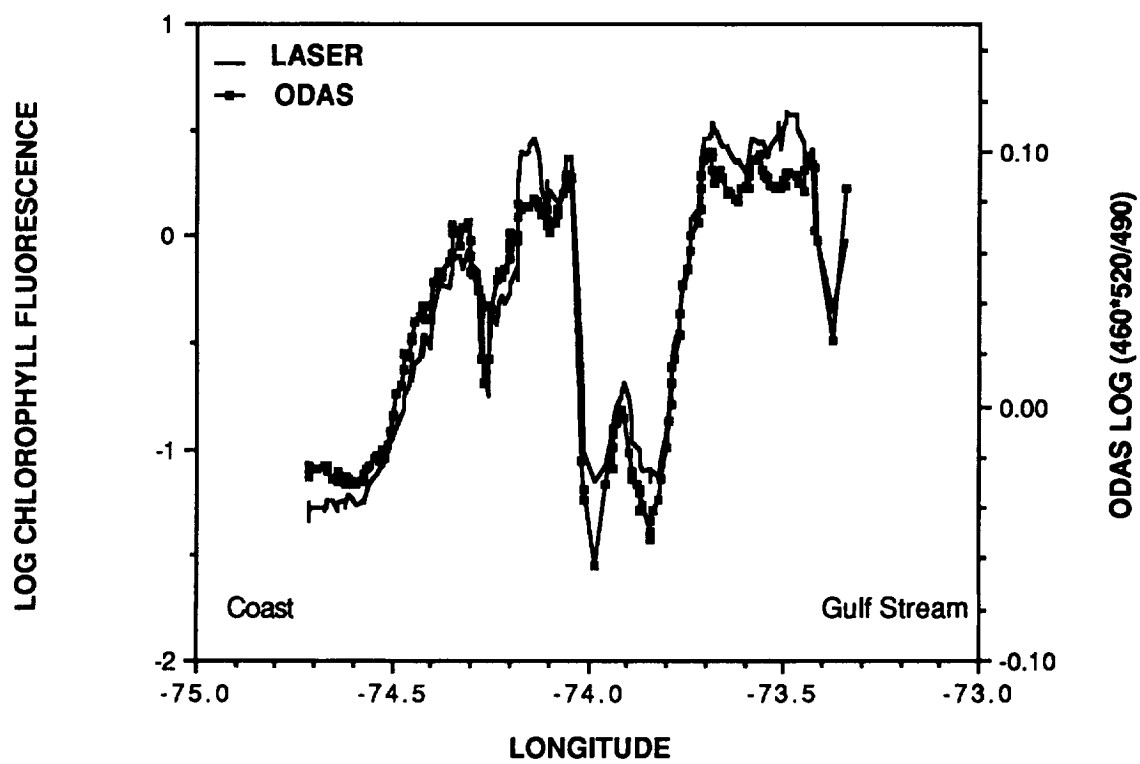


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1989 Biomonitoring Station Data
Maryland and Virginia

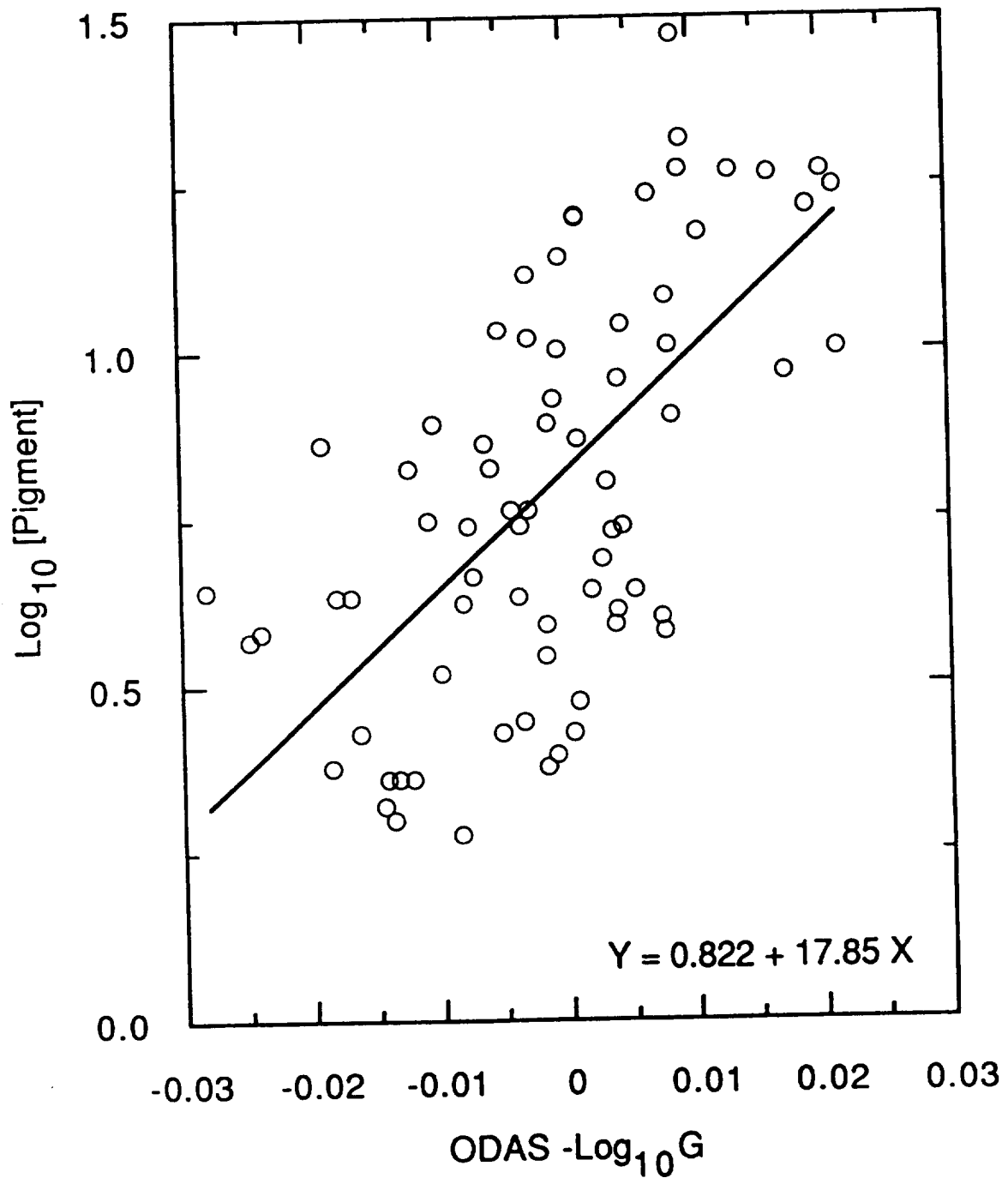


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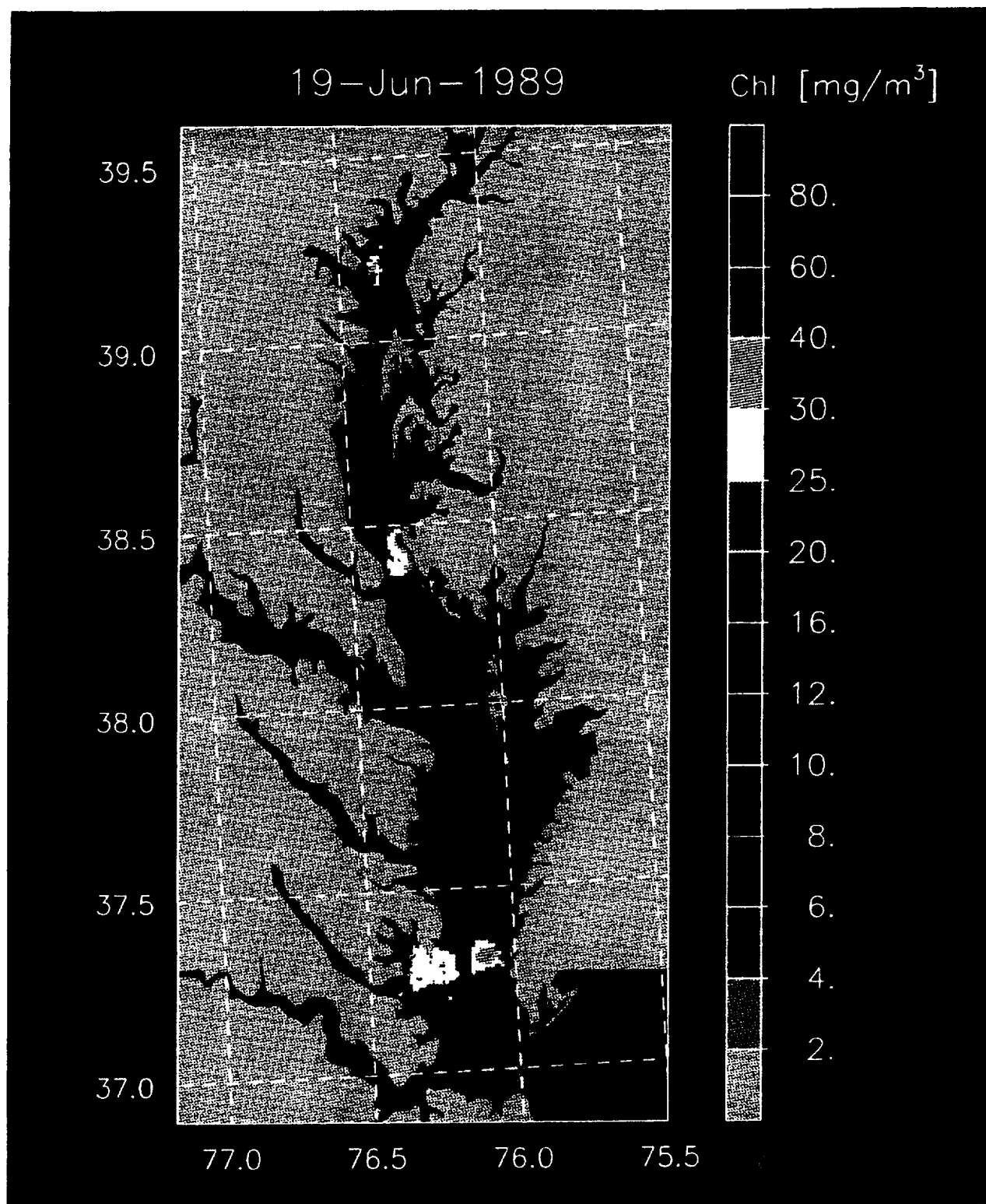


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